

The Spectral Line Shape of Exotic Nuclei

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Abstract

The quadrupole strength function of ^{28}O is calculated making use of the SIII interaction, within the framework of continuum-RPA and taking into account collisions among the nucleons (doorway coupling). The centroid of the giant resonance is predicted at ≈ 14 MeV, that is much below the energy expected for both isoscalar and isovector quadrupole resonances in nuclei along the stability valley. About half of this width arises from the coupling of the resonance to the continuum and about half is due to doorway coupling. This result is similar to that obtained in the study of giant resonances in light, β -stable nuclei, and shows the lack of basis for the expectation, entertained until now in the literature, that continuum decay was the main damping mechanism of giant resonances in halo nuclei [1].

A central subject in the study of the nuclear structure is that of the damping of vibrational motion (cf., e.g., [2,3]). The variety of relaxation processes may be divided in two broad categories, according to whether the energy of the excitation escapes from the system, or whether it is merely redistributed into other degrees of freedom within the system. In the first category we have the natural decay processes such as photon emission or particle emission. Widths due to photon emission are completely negligible if there are any competing damping mechanisms, but particle emission can be important. The second category includes a number of diverse mechanisms for spreading the strength function of the oscillation, depending on the particular degrees of freedom which are involved. First to mention are the single-particle degrees of freedom. These damp the vibrational motion, a phenomenon known as Landau damping, if their energy spectrum is dense near the collective excitation energy. Another damping mechanism corresponds to collisions between particles within the system. Quantum-mechanically, this mechanism appears when configurations having a more complex character mix into the simple single-particle single-hole (1p-1h) configurations that characterize the collective excitations. As a rule these collisions are more effective when they take place at the surface of the system. This is because density is lower and the Pauli principle is less effective in blocking final states. Also collective oscillations of the surface may be excited, effectively enhancing the collisional damping. The important role played by the surface in the purity of a nuclear vibration is particularly simple to see in the case of non-spherical systems. Under such conditions, the vibrational frequency depends on the orientation of the oscillations with respect to the axes of the system. This is the phenomenon of inhomogeneous damping. Particle-decay, Landau damping and inhomogeneous damping are present already at the level of mean field. Collisional damping implies processes which go beyond mean field. The study of vibrating exotic nuclei in general (cf., e.g., [4]) and of halo nuclei in particular gives new possibilities to the quest for the mechanisms active in the damping of nuclear motion. This is because due to the low-binding energy of the halo-nucleons, the role of damping through particle decay becomes very important in these nuclei, as compared with nuclei along the valley of β -stability. Also because of the large radial extension of the wavefunctions associated with the weakly bound nucleons, new sources of inhomogeneity are active, namely those which distinguish between core and halo excitations. Consequently the study of the spectral function of exotic nuclei constitutes a stringent test of theories of nuclear collective motion and of the associated damping processes.

In the present paper we shall study the quadrupole response of ^{28}O . The mean field was determined within the Hartree-Fock approximation and the properties of the quadrupole vibrations were worked out in the Random Phase Approximation, renormalized through the coupling to continuum configurations as well as with doorway states made up of a particle-hole excitation and a collective surface vibration. It will be concluded that while the continuum plays an important role in determining the properties of the linear response of the system, the corrections to the energy and width of the modes induced by the coupling of the vibrations to doorway states, not only play a role of similar importance to that played by the coupling to the continuum, but can change in a qualitative fashion the spectral strength distribution.

The spherical Hartree-Fock equations have been solved using a Skyrme III (SIII) effective interaction [5]. The resulting single-particle spectrum of bound levels and the associated mean field potential for both protons and neutrons are displayed in Fig. 1. Also shown in

Fig. 1 is the nuclear density associated with these results. A conspicuous halo of neutron matter is apparent in keeping with the fact that each of the four $d_{3/2}$ neutrons of the system has a binding energy of 1.1 MeV. This value is to be compared with the value of 30 MeV, that is, the binding energy of each of the least bound proton states, moving in the $1p_{1/2}$ orbital. Other Skyrme interactions (like SKM* or SGII) would give larger neutron binding energies and therefore, the neutron halo would be reduced or even absent.

Making use of the particle-hole basis associated with the single particle spectrum shown above, we have calculated the corresponding self-consistent continuum-RPA quadrupole strength function. The calculations were carried out in coordinate space as described in [7] and the corresponding results are shown in Fig. 2. Also shown in the figure is the unperturbed response function. Both strength functions exhaust about 95% of the energy weighted sum rule of the operator $\sum_{i=1}^A r_i^2 Y_{20}(\hat{r}_i)$. We obtain essentially the same result by solving the configuration space RPA matrix equation (discrete RPA) and by taking properly into account the coupling to the continuum configurations [8].

We can roughly divide the RPA strength function in three regions : a) The first region extends from 1.1 MeV to about 13 MeV and carries 22% of the EWSR. The sudden increase of the strength function at about 1.1 MeV and the shape of the low-energy peaks is essentially controlled by the coupling to the continuum associated with few unperturbed single particle configurations. In fact, we find that this part of the spectrum is dominated by transitions from the neutron $1d_{3/2}$ orbital to s- and d- levels lying in the continuum. This means that we deal with pure neutron modes, which by definition are in equal proportion of isoscalar and isovector character. In keeping with these results, both the RPA and the unperturbed response functions essentially coincide below 6 MeV; b) The second region lies in the energy interval 13 MeV - 19 MeV and accumulates approximately 55% of the EWSR. Because this part of the strength function corresponds to a single, well defined peak, we shall identify it with the giant quadrupole resonance (GQR) region. The fact that centroid of this resonance is at ≈ 16 MeV, that is, lower than expected from the energy systematics of the ISGQR ($\approx 63 A^{-1/3}$ MeV ≈ 21 MeV) and of the IVGQR ($\approx 130 A^{-1/3}$ MeV ≈ 43 MeV) in nuclei along the β -stability valley, testifies to the central role played by the halo nucleons in softening this resonance. Further evidence is provided by the fact that the contribution of the halo neutrons to the wavefunction of states within this region amounts to $\approx 60\%$, the contributions of neutron and proton core-excitations being $\approx 35\%$ and $\approx 5\%$ respectively. Note also that in the case of nuclei along the stability valley, protons and neutrons contribute essentially on equal footing to the GQR; c) The third region of the RPA-continuum strength function extends from 19 MeV up to 35 MeV and carries $\approx 16\%$ of the EWSR. Proton excitations are responsible for $\approx 70\%$ of the sum rule in this region, while neutron-core excitations contribute with $\approx 30\%$.

Within the framework of the theory discussed above and making use of the corresponding results, we have included collisions among the nucleons in the quadrupole strength function, that is, we have coupled the continuum-RPA response function to vibrations of the nuclear surface. This is tantamount to coupling the RPA mode to “doorway states” (cfr. ref. [2]), containing an uncorrelated particle-hole excitation and a collective vibration of the nuclear surface [10]. As can be seen from Fig. 3, a qualitative, let alone quantitative, change takes place in the line shape due to doorway coupling. The most important changes are connected with the parameters defining the giant resonance. In fact the centroid of the GQR is lowered

by ≈ 2 MeV, to an energy of 14 MeV, while the width of the giant resonance is increased from its value of 4 MeV at the continuum-RPA level, to 10 MeV. These results are model independent, and reflect the long wavelength behaviour of the surface vibrations of halo nuclei.

Below 1.5 MeV two discrete peaks become evident. These results are model dependent, being very sensitive to details of the residual interaction. Consequently, they have to be critically interpreted, as possible although not unique fingerprints of doorway coupling. Anyhow, the appearance of these two low-lying peaks is due, in the present case, to the fact that the real part of the quadrupole vibrations self-energy arising from doorway coupling lowers the energy of the transitions $1d_{3/2} \rightarrow 3s_{1/2}$, $1d_{3/2} \rightarrow 2d_{5/2}$, $1d_{3/2} \rightarrow 2d_{3/2}$ (which together exhaust about half of the total strength below 3 MeV), and brings two states based essentially on these configurations to an energy below particle threshold. The evolution of the properties of these states at different levels of the calculation, namely unperturbed particle-hole response, continuum-RPA, and continuum-RPA plus doorway coupling are displayed in Table 1. Particularly illuminating is the fact that the value of the imaginary part of the self-energy associated with the lowest states is considerably reduced introducing the coupling of the modes to doorway states, fingerprint of the lowering in energy acted on these states by the real part of these couplings. In the region of the GQR, doorway coupling has also a conspicuous effect. In particular, the centroid of the GQR is lowered by ≈ 2 MeV to an energy of the order of 14 MeV. Furthermore, the FWHM of the GQR changes from a value of ≈ 4 MeV at the continuum-RPA level, to ≈ 10 MeV including collisions.

From the example of this calculation, we may conclude that in general, the coupling to doorway states will change in a qualitative way the strength function of vibrational states also in exotic nuclei, for which the coupling to the continuum was expected up to now to be the main mechanism of damping.

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REFERENCES

- [1] H. Sagawa, N. Van Giai, N. Takigawa, M. Ishihara and K. Yazaki, Z. Phys. **A351**, 385 (1995); I. Hamamoto and H. Sagawa, Phys. Rev. **C53**, R1492 (1996).
- [2] G.F. Bertsch, P.F. Bortignon, R.A. Broglia, Rev. Mod. Phys. **55**, 287 (1983).
- [3] G.F. Bertsch, R.A. Broglia, *Oscillations in Finite Quantum Systems* (Cambridge University Press, Cambridge, 1994).
- [4] Proceedings of the Third International Conference on Radioactive Nuclear Beams, East Lansing, Michigan, 24-27 May 1993, ed. by D.J. Morrissey, Editions Frontières, Gif-sur-Yvette, 1993.
- [5] The calculations have been carried out as in ref. [6] to which we refer the reader for details except that we now calculate the mean field unoccupied levels at positive energies by putting the system inside a box of radius 25 fm instead of diagonalizing the mean field on a harmonic oscillator basis.
- [6] G. Colò, N. Van Giai, P.F. Bortignon, R.A. Broglia, Phys. Rev. **C50**, 1496 (1994).
- [7] K.F. Liu and N. Van Giai, Phys. Lett. **65**, 23 (1976).
- [8] If we do not include the coupling to the continuum we obtain the results of ref. [9].
- [9] M. Yokoyama, T. Otsuka and N. Fukunishi, Phys. Rev. **C52**, 1122 (1995).
- [10] The collective vibrations included are the isoscalar 2^+ , 3^- and the isovector 1^- states with more than 1% of the total strength and energy below 10 MeV, and with more than 2% of the total strength and energy between 10 and 20 MeV.

FIGURES

FIG. 1. Neutron and proton single-particle levels in ^{28}O , obtained within the Hartree-Fock approximation by using the effective interaction SIII. The Hartree-Fock mean potential is also shown in the figure. Making use of these results the density of the system has been also calculated and is displayed by a continuous curve on top of the figure. The proton (dotted curve) and neutron (dashed curve) contributions are also shown.

FIG. 2. Continuum-RPA results for the quadrupole response of the nucleus ^{28}O , obtained self-consistently with the interaction SIII, are displayed with the full line. The dashed line shows the unperturbed response.

FIG. 3. Results of RPA plus continuum and doorway coupling for the quadrupole response of ^{28}O (full line). For comparison, also the continuum-RPA results (dashed line) already shown in Fig. 2, are displayed.

TABLES

TABLE I. Evolution of the energy of the two sharp states in the very low energy region of the spectrum. Results associated with the unperturbed discrete response, continuum-RPA and continuum-RPA plus doorway coupling are shown in the upper, middle and lower section of the table.

Unperturbed response		
Transition Energy [MeV]	Energy [MeV]	Percentage of Strength
$1d_{3/2} \rightarrow 3s_{1/2}$	1.60	3.3
$1d_{3/2} \rightarrow 2d_{5/2}$	2.17	1.3
$1d_{3/2} \rightarrow 2d_{3/2}$	2.19	2.2
Continuum-RPA		
$1d_{3/2} \rightarrow 3s_{1/2}$	1.31-i0.18	1.8
$1d_{3/2} \rightarrow 2d_{5/2}$	1.82-i0.34	1.0
$1d_{3/2} \rightarrow 2d_{3/2}$	1.82-i0.34	0.7
Continuum-RPA plus doorway coupling		
$1d_{3/2} \rightarrow 3s_{1/2}$	0.78-i0.01	2.3
$1d_{3/2} \rightarrow 2d_{5/2}$	1.15-i0.02	0.6
$1d_{3/2} \rightarrow 2d_{3/2}$	1.15-i0.02	1.1

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